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Cite as: Phys. Teach. **58**, 182 (2020); https://doi.org/10.1119/1.5145411
Published Online: 19 February 2020

Enrique Arribas, Isabel Escobar, Raquel Ramirez-Vazquez, Carmen del Pilar Suarez Rodriguez, Jesus Gonzalez-Rubio, and Augusto Belendez

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Enrique Arribas, Isabel Escobar, and Raquel Ramirez-Vazquez, University of Castilla-La Mancha, Albacete, Spain, and Associated Centre of Albacete, National Distance Education University (UNED), Albacete, Spain
Carmen del Pilar Suarez Rodriguez, Autonomous University of San Luis Potosi, Tamazunchale, San Luis Potosí, Mexico
Jesus Gonzalez-Rubio, Associated Centre of Albacete, National Distance Education University (UNED), Albacete, Spain, and Medical Science Department, University of Castilla-La Mancha, Albacete, Spain
Augusto Belendez, University of Alicante, San Vicente del Raspeig, Alicante, Spain

We believe that a natural focus of the physics education research community is on understanding and improving students' learning in our physics courses. Due to the increase in technology, we can bring laboratory experiments closer to our students. It is necessary to update our laboratories technologically to get closer to the world in which our students live. With this in mind, we have considered the magnetic field created by a linear quadrupole and we have studied its dependence on distance, *n* being the exponent of distance. The main objective of this exercise is for our students to discover that the exponent *n* is very close to –4. The purpose of this work is to show that a laboratory is a powerful tool that increases significant learning under three conditions: 1) the practice must not be too sophisticated; 2) students must handle objects in the lab; and 3) the practice must be scientifically accurate, including the fitting using the least-squares approximation, and the following and necessary error calculation. We provide this practice so that all interested physics teachers can use it and adapt it to their specific laboratory.

Background information

Over the last decade, due to the accelerated growth of the smartphone market, users demand different functionalities that meet their needs, and they use smartphones not only to make phone calls and send messages but also for multiple activities. Smartphones have several internal sensors that allow us to detect movements, orientation, proximity, luminosity, gravity, environmental conditions, and to gather information facilitating their use.[1,2] For instance, the magnetic sensor based on the Hall effect allows us to know the three components of the magnetic field.[3]

With the emergence of technology, we can bring laboratory experiments closer to our students. Mobile devices can provide meaningful assistance to users in their work, study, and entertainment. They have been widely used in recent years within the process of instruction in different disciplinary fields,[4–14] although the effects on learning and the purpose given to them in the classroom are still being studied. Furthermore, smartphones are becoming the data recorders of portable physics laboratories for a variety of measurements in astronomy, mechanics, thermodynamics, electromagnetism, and optics among others, either using the internal sensors of cell phones or diverse applications.[15–24]

We are mainly interested in how the smartphones used for performing a physics laboratory practice influenced the traditional learning of electromagnetism. Bearing this in mind, in this work we are going to focus on the design of a laboratory experience to measure the dependence of the magnetic field of a quadrupole on distance employing a smartphone.

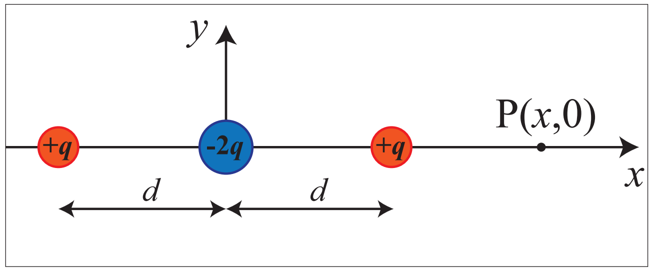

Fig. 1. A linear electric quadrupole is formed by two opposite electric dipoles, *d* being the separation between the charges and P(*x*, 0) the point where the electric field is wanted to be calculated.

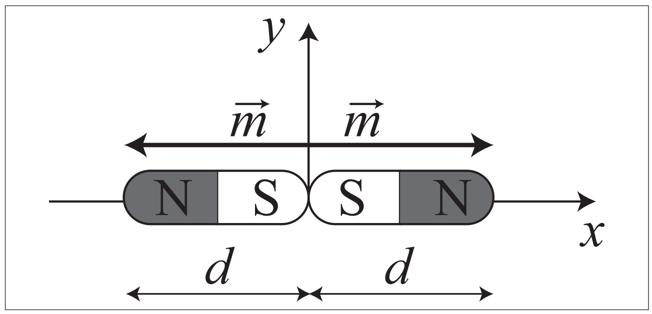

Fig. 2. A linear magnetic quadrupole is formed by two opposite magnetic dipoles obtaining a system with zero magnetic dipole moment, *m* being the magnetic dipole moment vector of each magnetic dipoles.

Basic theory

A linear electric quadrupole is a neutral charge system, formed by three charges: one with a value $-2q$ located at the origin of coordinates and two charges of value $+q$ located symmetrically on the x-axis, one at the point $(-d, 0)$ and the other at $(+d, 0)$ as shown in Fig. 1. The total width of the system is $2d$. The electric field of this quadrupole at an arbitrary point of the plane P has two components: one radial and the other transversal. For greater simplicity, we will consider the point P to be on the x-axis at a distance x from the origin of coordinates as indicated. The electric field of this neutral charge system can be obtained by using the electric field of two opposite dipoles, one centered on $(-d/2, 0)$ and the other one on $(+d/2, 0)$ or, analogously, by applying the superposition principle to three point charges, as shown in Fig. 1. The x-component of the electric field is

 DOI: 10.1119/1.5145411

$$E_x = \frac{kq}{(x-d)^2} - \frac{2kq}{x^2} + \frac{kq}{(x+d)^2}. \qquad (1)$$

Through straightforward calculations (using the binomial theorem, for example) and assuming that $x >> d$, the x-component of the electric field of the quadrupole is

$$E_x = \frac{6kpd}{x^4}, \qquad (2)$$

p being the electric dipole moment of each of the two dipoles, $p = qd$, and k the Coulomb's constant.

In fact, we want to study a magnetic quadrupole, for which two magnetic dipoles will be used with the two south poles together, at the origin of coordinates, and with their north poles placed at the points $(-d, 0)$ and $(+d, 0)$, obtaining a system with zero magnetic dipole moment (see Fig. 2).

A similar expression to Eq. (1) can be written for the x-component of the magnetic field vector, replacing the variables appropriately: k for μ_0, and p for m, μ_0 being the magnetic permeability of vacuum and m the magnitude of the magnetic dipole moment vector of both magnets, which have previously had to be carefully selected so that they are equal. Then the total magnetic dipole moment is canceled just as in the electrostatic case, and the quadrupole moment survives, yielding

$$B_x = \frac{6\mu_0 md}{x^4}. \qquad (3)$$

It is very important that both magnets have the same geometrical and magnetic characteristics.

Experimental procedure

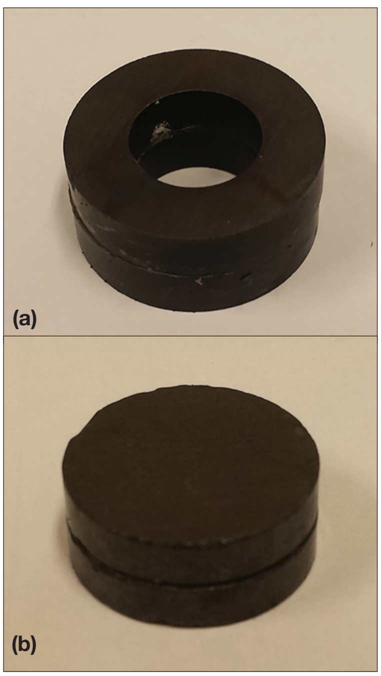

Fig. 3. Magnetic quadrupoles used: (a) Neodymium rings of 3.5 cm of diameter; (b) ceramic magnets of 1.5 cm of diameter.

First, the magnetic quadrupole must be constructed; this is a system composed of two identical dipoles of equal but oppositely directed moment so that the magnetic moment of the system is zero [see Figs. 2, 3(a) and 3(b)]. It is important to take into account that two identical magnets must be chosen as possible in order to obtain results in line with the theoretical prediction.

We need to install an application that measures the three spatial components of the magnetic field on the smartphone. Out of all the apps that allow us to make these measurements on the internet, we recommend the Magnetometer app for iOs, and Physics Toolbox Sensor Suite app by Vieyra Software for smartphones with Android operating system.

Fig. 4. The orientation of the spatial axes on a smartphone.

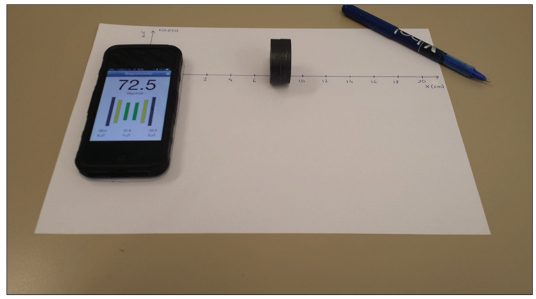

Fig. 5. Experimental assembly: a smartphone, a sheet of paper, and two identical magnets pasted by their two south poles.

Since the goal of the laboratory practice is to determine the dependency of the magnetic field on distance, we will consider only a component of the magnetic field, for example, the x-component.[15] In Fig. 4 the orientation of the spatial axes on a smartphone is shown. They can be determined through a small discovery process, which consists of bringing a small magnet near our phone from different directions and observing the component that varies in the app that measures the magnetic field.

Finally, the acquisition of data is completed as follows. The smartphone is placed on a sheet of paper and we draw the corresponding x- and y-axes of the phone passing through the magnetic sensor (see Fig. 5). Then, the y-axis should be oriented towards the geographic north in order to avoid the magnetic field background coming from the terrestrial magnetic field. If it is impossible to exactly cancel this background, it should be subtracted from our measurements. And lastly, the magnetic quadrupole is placed at different distances and we can write down the value of the x-component of the magnetic field provided by the application.

Results

In this section, we will analyze the results obtained with an iPhone 5 smartphone with the Magnetometer application for two magnetic quadrupoles, that is, they are composed of magnets of different forms and magnetic moments (see Fig. 3).

Figure 6 shows the graphical representation of the data

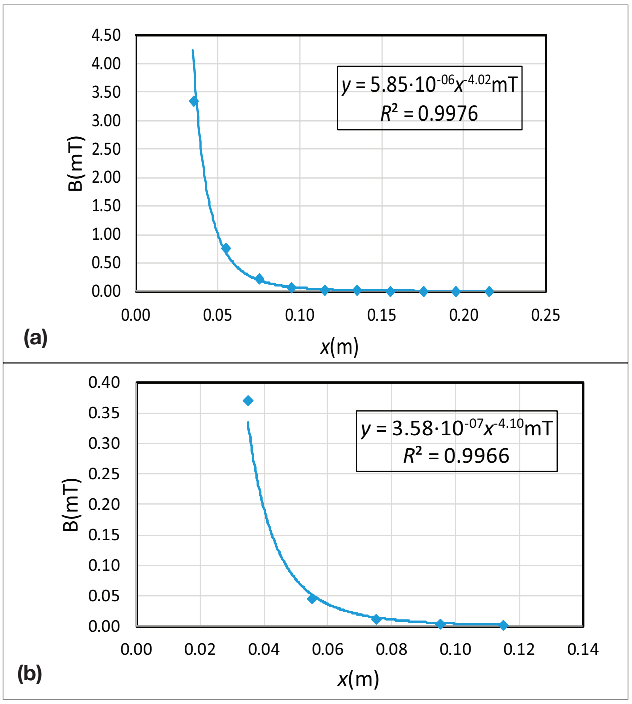

Fig. 6. (◆) Experimental measures of the magnetic field and (--) power fitting of the experimental measures for (a) magnetic quadrupole composed of two neodymium rings; (b) magnetic quadrupole composed of two ceramic magnets.

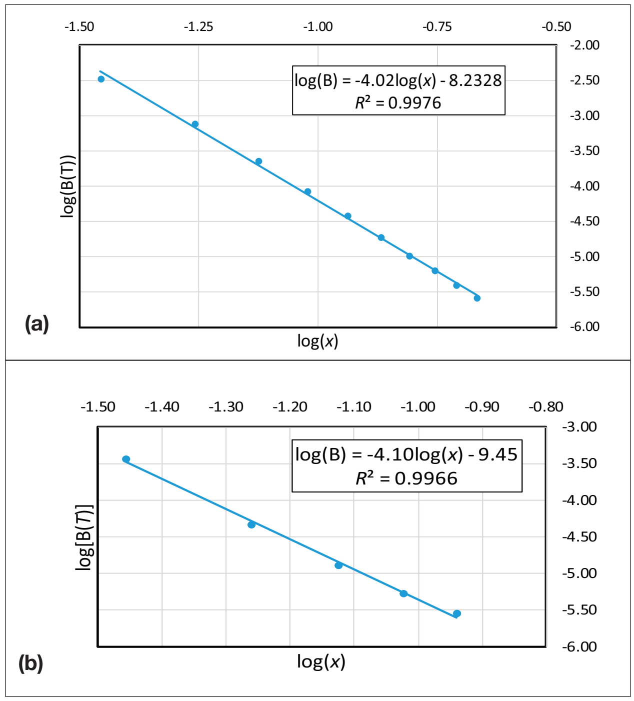

Fig. 7. (●) Decimal logarithms of the experimental data (--) linear fitting of the experimental measures for (a) magnetic quadrupole composed of two neodymium rings; (b) magnetic quadrupole composed of two ceramic magnets.

taken with the magnetic sensor of the smartphone for the *x*-component of the magnetic field *B*, as a function of the *x*-distance. This figure also shows the trendline of the experimental data with Excel, using the option "power," the equation that fits the experimental data (*B* as a function of *x*), and the squared correlation coefficient R^2. In the case of Fig. 6(a) we have used a magnetic quadrupole composed of two neodymium rings [Fig. 3(a)]. We have placed the quadrupole 2 to 20 cm away from the smartphone. In Fig. 6(b) the results have been obtained with a magnetic quadrupole composed of two ceramic magnets [see Fig. 3(b)]. In this case, we have placed the quadrupole 2 to 10 cm away from the smartphone because the magnetic sensor of the smartphone didn't detect the magnetic field of this quadrupole for bigger distances.

According to the theoretical model [Eq. (3)], the *x*-component of the magnetic field of the quadrupole is given by

$$B_x = 6\mu_0\, m d x^n\,. \tag{4}$$

The value of *n* from the experimental data is approximately −4; this is −4.02 (ring quadrupole) and −4.10 (ceramic quadrupole), which is in total agreement with the theoretical prediction when we consider error calculation (see Table I). Besides, it is possible to observe that both measurements with different quadrupoles have a squared correlation coefficient very close to unit, 0.9976 (ring quadrupole) and 0.9966 (ceramic quadrupole).

On the one hand, an objective that is considered sufficient is to be aware that the exponent *n* is very close to minus four. On the other hand, error calculation is an important task in experimental works. For that reason, the students must carry out (calculate) an error analysis of the measurements and results, and they must fit the data using the least squares method for linear regression. Consequently, we must linearize the results obtained in Fig. 6, taking logarithms in Eq. (4), and the following linear expression is obtained:

Table I. Experimental results of the value of the exponent of *x* after the corresponding linear regression using least squares method.

	$n \pm \varepsilon_a(n)$	$\varepsilon_r(n)$
Ring quadrupole	−4.02 ± 0.07	1.7%
Ceramic quadrupole	−4.10 ± 0.14	3%

$$\log B_x = \log(6\,\mu_0\, md) + n \log x\,. \tag{5}$$

If we represent $\log B_x$ vs. $\log x$, we can obtain information about the exponent of *x* and its absolute error, through the slope of the linear fitting (see Fig. 7). In Table I, we show the results for the corresponding fitting by least squares to the two quadrupoles used in this practice.

As we can see from the results shown in Table I, the experimental values of the dependency of the magnetic field with the distance are compatible with the expected theoretical value.

The argument of the logarithm should be a dimensionless magnitude, although that fact is discarded here because it is not relevant. It is recommended to work in the International System of Units so as not to have problems with the interpretation of the results.

The students do not know Eq. (3); they are told that *B* is a function of a negative power of the variable *x*, which they themselves observe because when decreasing *x*, *B* increases. Therefore, students do not know that the exponent of *x* is −4, and they must obtain this result learning by discovery. In this way, students learn it in a highly significant way through their own experience in the laboratory. The physics laboratory allows meaningful learning as long as the practices are well designed out and not overly sophisticated.

Conclusions

A simple laboratory practice has been designed that allows first-year science and engineering (STEM) students to obtain results that are quite accurate and compatible with the underlying electromagnetic theory. For an exponent whose theoretical value must be –4, two very close experimental values are obtained: –4.02 ± 0.07 and –4.10 ± 0.14, with relative errors of 1.7% and 3%, which are quite small values for a physics laboratory of the first year, and without using especially complex devices to take the measurements.

In addition, students are motivated with the use of new technologies, introducing smartphones to measure the magnetic field through the sensor that these phones usually have, along with a suitable and free app. In fact, the most sophisticated device used is the smartphone, and since most students have one, the practice is also very cheap. The practices are done in groups of two students, so if someone does not have a smartphone, they can pair up with another student who does. Again, the smartphone (with its multiple sensors) and a free app suitable for measuring magnetic fields are shown as a very versatile and accurate tools in a laboratory of first-year physics.

Acknowledgments
AB thanks the "Generalitat Valenciana" of Spain (project PROMETEOII/2015/015). IE is grateful to the Ministry of Economy and Competitiveness for the help provided through the project DPI2015-66458-C2-1-R. EA thanks the Associated Center UNED Albacete for the facilities given for the use of its laboratory.

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